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Volcanological aspects of the northwest region of Paraná continental flood basalts (Brazil)

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Abstract. There has been little research on volcanological aspects of Paraná continental flood basalts (PCFBs), and all investigations have mainly been concentrated on the internal portions of the lava flows. Thus, this study describes for the first time morphological aspects of lava flows and structural characteristics caused by lava–sediment interaction in the northwestern PCFB province (NW-PCFB). Early Cretaceous (134 to 132 Ma) tholeiitic rocks of the PCFB were emplaced on a large intracratonic Paleozoic sedimentary basin (Paraná Basin), mainly covering dry eolian sandstones (Botucatu Formation). As this sedimentary unit is overlain by the basic lava flows of the PCFB, the interaction of lavas and unconsolidated sediments resulted in the generation of fluidal peperites. This aspect is significant because it shows that restricted wet environments should have existed in the Botucatu desert. The peperite zones of the NW-PCFB are associated with compound pahoehoe-type (P-type) flows and are always related to the first volcanic pulses. These flows have dispersed vesicles and sand-filled cracks in their base and top borders, as well as the presence of interlayered sandstones with irregular contacts and varied thicknesses. It is remarkable that, to the best of current knowledge, only in this area of the whole PCFB did the volcanic activity start with low-Ti basalt flows of Ribeira type ($TiO_2 < 2.3$ wt %), which are scarce in the province.

1 Introduction

Continental flood basalts (CFBs) are the result of brief igneous events that may last only a few million years or less, producing vast volumes of lavas and intrusive rocks (Coffin and Eldholm, 1994). As emphasized by Self et al. (1997) and Skilling et al. (2002), the physical volcanology of CFBs has received relatively little attention, since many previous studies have tried to understand their petrological, geophysical, geodynamical, and geochemical features, identifying possible mantle sources, crustal or mantle contaminants, and low-pressure magma evolution of the basalts generated in these magmatic processes.

Initial studies on physical volcanology of CFBs have been devoted to mainly describe the flow architectures as well as the mechanisms involved in their emplacement. One of the first provinces where this kind of investigation was accomplished is the Columbia River basalts, whose flows are mainly compound pahoehoe (Riedel and Tolan, 1992), presenting also peperites as a result of the interaction of lava flows with unconsolidated sedimentary deposits (Riedel, 1998). For the Deccan volcanic province, Duriaiswami et al. (2008) described rubbly pahohoe flows in upper stratigraphic unities, whereas Boundre et al. (2004) emphasized the occurrence of compound pahohoe in the lower and middle sequences, as well as peperites (only just at the edges of the province). Regarding the Ferrar volcanic province, Antarctica, the peperites formed by mingling of basalt flows

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with coal, as well as where these lavas encountered continental sedimentary successions of the Mawson Formation (McClintock and White, 2002).

The lava flows of the Paraná continental flood basalt (PCFB) province were emplaced in the Early Cretaceous on a large intracratonic sedimentary basin (Paraná Basin) that began subsiding in the early Paleozoic, covering sandstones of the Botucatu Formation (dry eolian system in extensive fields of dunes). Although considerable progress on the geochemical, geochronological, geophysical, and geodynamical aspects of the PCFB, as well as about the characteristics of the mantle sources involved in the magmatism, has been made, very little is known about the physical volcanology of this event. The geochemical and petrological studies have mainly been concentrated in the internal portions of the lava flows, where supposedly the rocks have no significant changes from their original geochemical composition. This fact partially explains the restricted number of studies that typify the flows and their internal structures, although PCFB constitutes one of the largest volcanic provinces of the world. Another important aspect that does not encourage investigations on this subject is the lack of well-preserved exposures due to weathering under the tropical–subtropical humid climate and the discontinuity of the outcrops.

The early studies that have attempted to understand the lava–sediment interaction in the PCFB were concentrated on exposures from its southern and central areas, and mainly focused on the peperite occurrences. The investigations were carried out by Petry et al. (2007) and Waichel et al. (2007, 2008) for basalt flows and Luchetti et al. (2014) for basalt and rhyolite flows or ignimbrites. According to these workers, the textures of the mafic peperite breccia vary from globular to amoeboid (anhedral form), while the rhyolitic ones range from blocky (also called jigsaw-fit) to irregular form (subhedral form). Regarding the peperite origin of the PCFB flows there is some controversy. For Waichel et al. (2007, 2008) these structures are the result of mixing and mingling processes involving lavas and unconsolidated or poorly consolidated wet sediments, agreeing with the usually proposed models for other provinces (White et al., 2000; Cas et al., 2001; Dadd and Van Wagoner, 2002; Skilling et al., 2002). However, Petry et al. (2007), following the reasoning of Jerram and Stollhofen (2002), explain that some peperites of the PCFB (southern region) were not originated in a wet environment, requiring only lava overspreading the lee side of the dunes (slopes $\sim 30°$).

In this context, the main goal of this study is to describe the morphological aspects of lava flows and the structural characteristics caused by lava–sediment interaction in the northwestern PCFB (NW-PCFB; Fig. 1), as well as to discuss the mechanisms involved during the extrusion processes. In addition, we present new geochemical data in order to establish the accurate stratigraphy of the flows in the area. It is important to stress that the investigated region has a distinctive geomorphology, with flat topography, encompassing some geological faults, rare outcrops, and significant erosive processes due to the tropical humid climate. These characteristics make it much more difficult to recognize the volcanological features, in comparison to other areas of the PCFB, as well as in locations where the eruptions occurred more recently (e.g., Columbia River) and/or the rocks are very well preserved (e.g., Etendeka province – Namibia).

2 Geological setting

The tholeiites of the PCFB province are of Early Cretaceous age and were emplaced on a large intracratonic Paleozoic sedimentary basin (Paraná Basin) covering $1\,500\,000\,km^2$ that developed between the Ordovician and the Cretaceous (Fig. 1). This basin is located in terrains of the South American platform, which were extensively affected by the tectonic, metamorphic, and magmatic events of the Brasiliano–Pan-African orogenic cycle, whose most important accretion episodes are the ones between 650 and 500 Ma (e.g., Cordani et al., 2003).

The PCFB occupies an area of about $917\,000\,km^2$ (encompassing $\sim 75\,\%$ of the Paraná Basin), covering large areas in south Brazil, Argentina, Uruguay, and Paraguay, with an estimated original volume in excess of $600\,000\,km^3$ (Frank et al., 2009). Associated with the volcanic activity there was intrusive magmatism, represented by sills, which outcrop mainly in the eastern and northeastern Paraná Basin, and dyke swarms (Ponta Grossa, Serra do Mar, and Florianópolis; Piccirillo et al., 1990; Raposo et al., 1998; Deckart et al., 1998; Almeida et al., 2012, and references therein).

Geochronological data (based on $^{40}Ar\,/\,^{39}Ar$ method), combined with paleomagnetic studies, show that the main volcanic activity of the PCFB occurred within a short time interval between 133 and 132 Ma (Renne et al., 1992; Turner et al., 1994; Ernesto et al., 2002). Most recently, Thiede and Vasconcelos (2010) placed PCFB extrusion at 134.6 ± 0.6 Ma, concluding that the duration of the PCFB volcanism was less than 1.2 Ma. Baddeleyite/zircon LA-ICP-MS (laser ablation-inductively coupled plasma-mass spectrometry) and U-Pb age dating on felsic volcanic rocks from the PCFB yielded an age of 134.3 ± 0.8 Ma (Janasi et al., 2011), confirming the idea that this magmatic event was emplaced over a short period of about 1–2 Ma.

Previous geological and geochemical studies (e.g., Bellieni et al.,1984; Piccirillo and Melfi, 1988; Peate et al., 1992; Marques et al.,1999) allowed the division of the PCFB into two main regions: (1) the southern PCFB is characterized by dominant tholeiitic basalts with dominantly low Ti (LTi; $TiO_2 \leq 2$ wt %), low concentrations of incompatible elements – such as P, Ba, Sr, Zr, Hf, Ta, and Y – and light REEs; (2) the northern PCFB is characterized by prevalent tholeiites with relatively high concentrations of TiO_2 (HTi; $TiO_2 > 2$ wt %) and incompatible elements. These studies also showed that rare LTi basalts are found in the northern

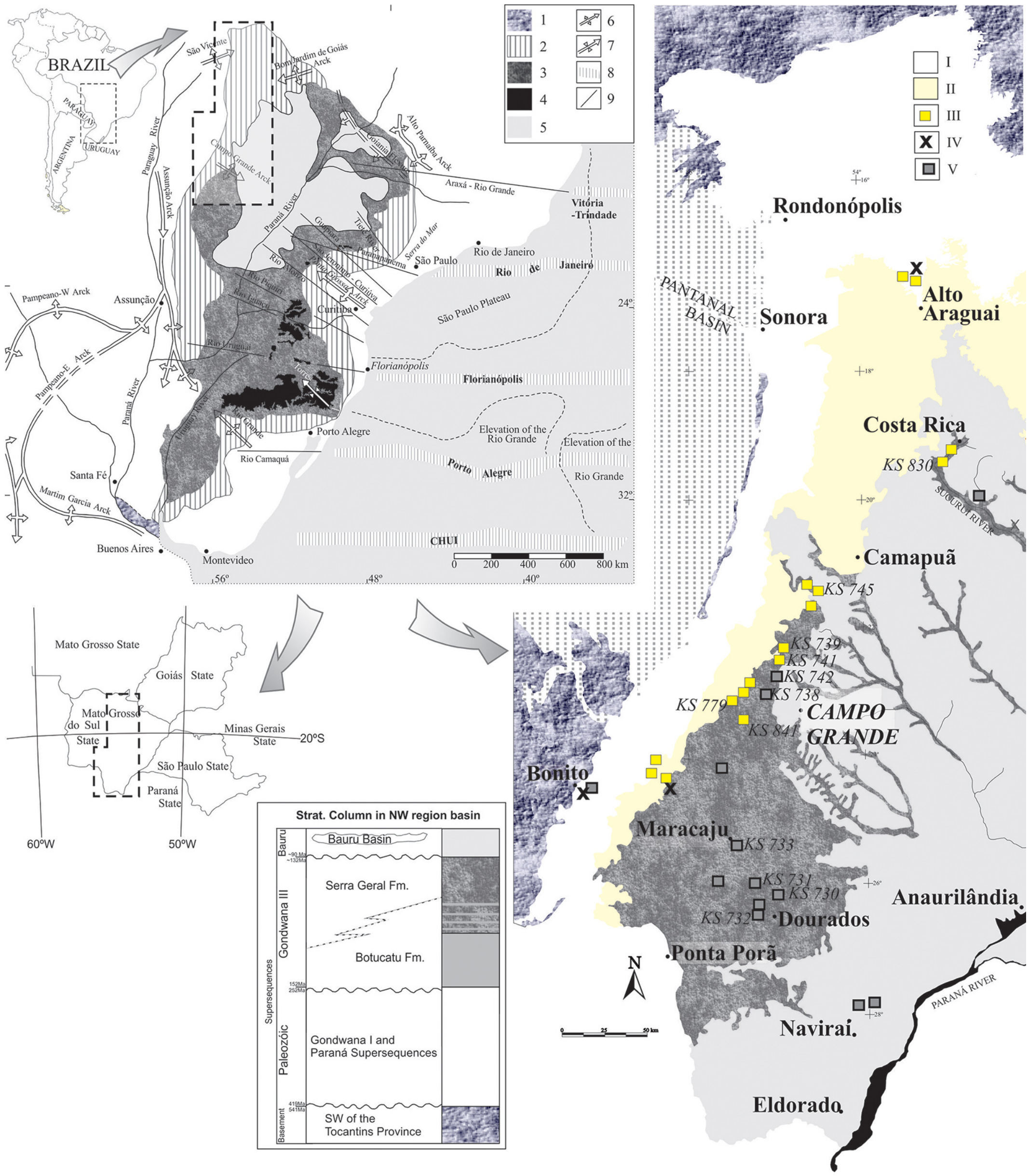

Figure 1. Simplified geological map (CPRM, 2006) of the investigated area indicating sample locations and the stratigraphic column of the area. The geological map of the Paraná Basin (Nardy et al., 2002) is also shown. 1 – Tocantins province (basement); 2 – pre-volcanic sedimentary rocks; 3 – basalts (PCFB); 4 – acid volcanics (PCFB); 5 – post-volcanic sedimentary rocks; 6 – anticlinal structure; 7 – synclinal structure; 8 – oceanic lineaments; 9 – continental lineaments; I – Paleozoic sequences of the Paraná Basin; II – Botucatu Formation; III – Ribeira magma-type samples; IV – Paranapanema magma-type samples; V – Pitanga magma-type samples.

PCFB and that scarce HTi basalts are encountered in the southern PCFB.

According to Peate et al. (1992), the basalt rocks from PCFB can be grouped into six distinct magma types based on titanium, incompatible trace elements (Sr, Y, and Zr) and their ratios, which were also used in order to minimize fractional crystallization effects. The HTi basalts were organized into three groups: Urubici ($TiO_2 > 3.3$ %; $Sr > 550$ ppm; $Ti / Y > 500$), Pitanga ($TiO_2 > 2.8$ wt %; $Sr > 350$ ppm; $Ti / Y > 350$), and Paranapanema ($1.7 < TiO_2 < 3.2$ wt %; $200 < Sr < 450$ ppm; $Ti / Y > 330$). The LTi basalts were also organized into three groups: Gramado ($0.7\,\% < TiO_2 < 2$ wt %; $140 < Sr < 400$ ppm; $Ti / Y < 300$), Esmeralda ($1.1 < TiO_2 < 2.3$ wt %; $Sr < 250$ ppm; $Ti / Y < 330$), and Ribeira ($1.5 < TiO_2 < 2.3$ wt %; $200 < Sr < 375$ ppm; $Ti / Y > 300$). It is important to note that in comparison to the detailed geochemical analyses carried out on other magma types of the PCFB there have been few prior geochemical studies done on Ribeira basalts, especially those outcropping at the northwestern border of the province. In this study, we also present new whole-rock analysis of major, minor, and lithophile trace elements for a significant number of Ribeira magma-type samples.

Throughout the province, the lavas often cover the Botucatu Formation of the Paraná Basin, which is interpreted as a typical dry eolian system (e.g., Scherer et al., 2000), reaching an area of approximately 1300 000 km^2. The sedimentation process initiated at the Mid-Jurassic (Leonardi and Oliveira, 1990) and lasted until the Early Cretaceous. The fine–medium-grained and well-selected reddish sandstones are composed almost entirely of quartz, presenting textural bimodality. Medium to large tabular cross bedding is a common feature.

In that environment, the lavas of the PCFB first buried the areas between dune fields; then filled the inter-dune areas; and finally covered largest eolic desert accumulations. The contact between the two geological formations is concordant and abrupt, with a lack of paleosols, which might show any depositional hiatus between the two events. Furthermore, the frequent sandstone intercalations, present at the bottom and intermediate levels of the volcanic piles, evidence that the two geological unities developed contemporaneously during the Early Cretaceous. The intermittent character of both geological formations is evidenced by the interlayered sedimentary rocks, whose thicknesses vary from a few centimeters to several meters.

3 Analytical methods

Thirty-six samples were collected in the NW-PCFB and analyzed for major, minor, and some trace elements (Cr, Ni, Sr, Y, Zr, and Nb) by X-ray florescence (XRF), at the Universidade Estadual Paulista (UNESP, Brazil). A subset of 12 samples was selected for rare earth elements (REEs; La, Ce, Nb, Sm, Eu, Gd, Dy, Ho, Er, Yb, and Lu) analysis by inductively coupled plasma mass spectrometry (ICP-MS) at the Universidade Estadual de Campinas (UNICAMP, Brazil). Sample locations are shown in Fig. 1.

Prior to analysis, unaltered parts of every rock were covered with a cloth and crushed to smaller pieces with a rock hammer. Selected portions were cleaned with distilled water in ultrasonic bath and ground to thin powder with a tungsten carbide mill for XRF analysis and with an agate mill for ICP-MS analysis. The technique used is that described by Nardy et al. (1997), Machado et al. (2009), Cotta and Enzweiler (2012), and Rocha-Júnior et al. (2013). In general, XRF relative accuracy for major and minor elements is ± 1 %, whereas for trace elements it is within ± 3 %. For the REEs determined by ICP-MS the analytical uncertainties is typically better than 5 %.

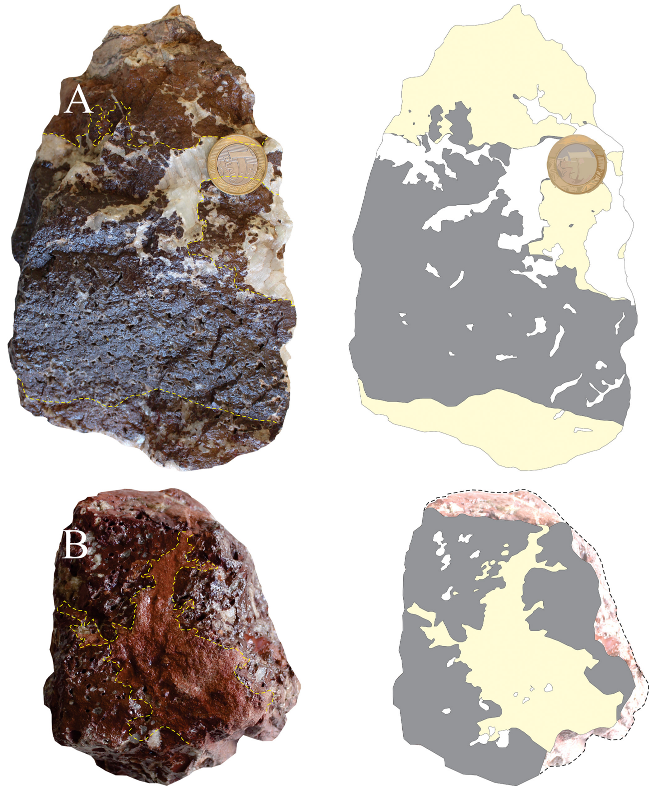

Figure 2. Photographs and schematic illustrations of large and small clasts in peperite zone showing vesicles and stretched vesicles (filled by calcite in **a** and fluidal margins in **b**). Coin diameter = 27 mm.

4 Geological aspects of the investigated area

In the NW-PCFB the Botucatu sandstones are widely overspread (Fig. 1), presenting medium cross bedding and no distinctive characteristics in comparison to the reported ones for the other areas of the Paraná Basin (e.g., Scherer et al., 2000). The sediment flux measurements performed in three outcrops indicate sand movements to the north-northeast.

Since the first stages of basalt lava emplacement were concurrent with those related to the end of Botucatu sand deposition and diagenesis, several features of lava–sediment interaction were generated in the investigated area. The peperite zones are always associated with the first basalt flow and reach up to 2 m thick, whose host is composed of very fine grained sandstone, with low-angle stratification (5°). This reddish and silicified sedimentary rock contains irregular clasts of volcanic rock, varying from submillimeter-to-millimeter size to 30 cm. The larger ones (centimeter-to-decimeter size) are vesicular and in general characterized by irregular contacts and fluidal margins (Fig. 2), whereas the smaller ones (submillimeter-to-millimeter size) are subrounded, and some of them exhibit quenched rims.

The peperites are amoeboid-shaped and may extend up to 80 m in a unique outcrop. Based on the relative proportions

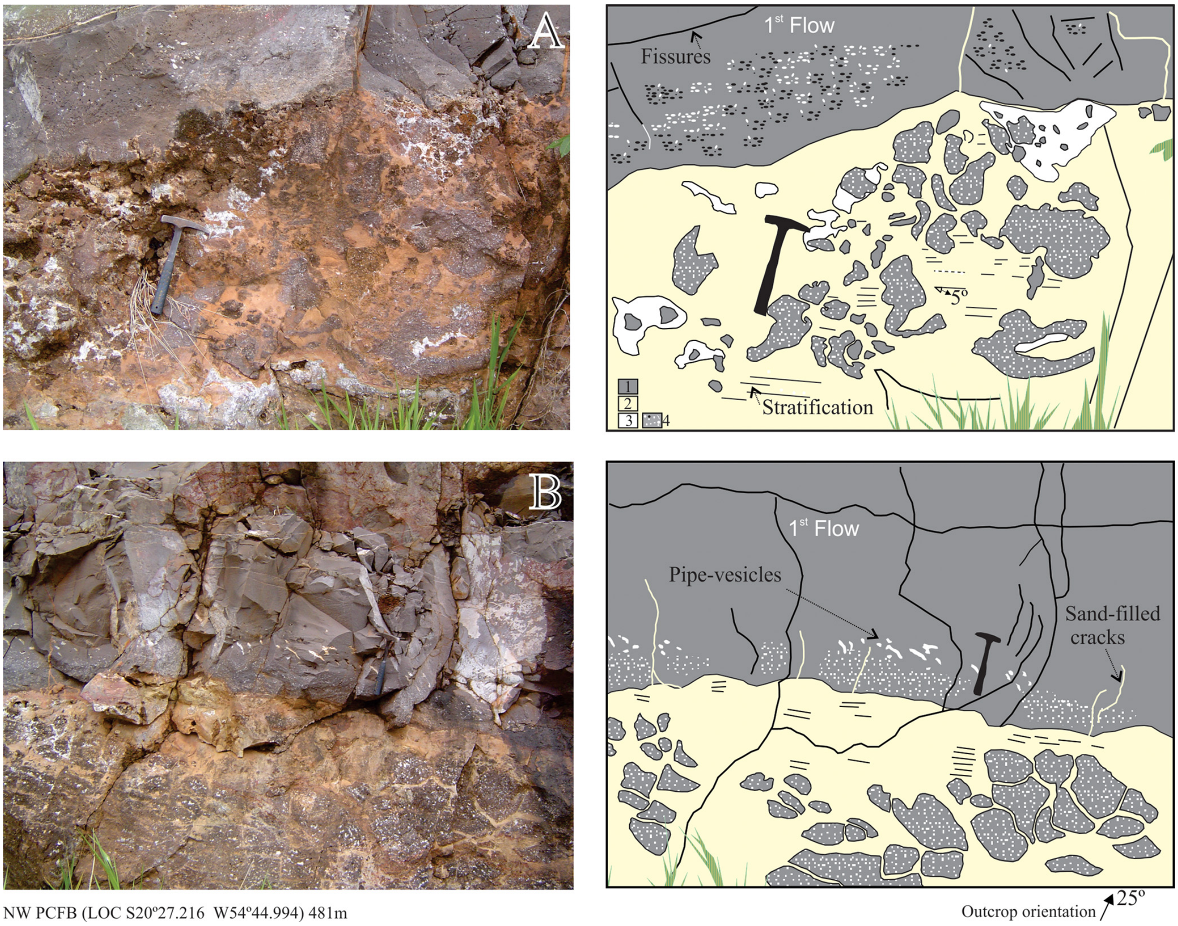

Figure 3. Peperite layers showing basalt volcanic clasts hosted in eolian sandstone. **(a)** Peperite texture in very fine grained sandstone with cross-bedding, low-angle stratification (5°) with juvenile volcanic clasts of amoeboid shape. **(b)** Pipe vesicles and sand-filled cracks in the base of the sequences.

Figure 4. Rope surface identified on the top of the compound pahoehoe flows outcropping near Nivaraí village.

of host sediment and juvenile clasts, these peperites are classified in the literature as dispersed (e.g., Skilling et al., 2002).

It is also important to emphasize the presence of aligned vesicle zones (up to 1 m thick) parallel to the contact with sedimentary host rock or even dispersed in it. Pipe vesicles are also found (Fig. 3), indicating an apparent direction of 25° NE for the lava flow. The vesicles may achieve 2 cm in length, and there is no significant variation in their sizes if they are in the center or near the borders of the largest volcanic clasts, which may also present fractures. In general, the vesicles are filled with sediments of the host rock (Fig. 2b) or even by secondary minerals, such as calcite (Fig. 2a), natrolite or quartz, although some of them are empty. Stretched vesicles are often found, indicating plastic deformation, before complete cooling (Fig. 2).

The peperites are associated with pahoehoe flows and are only found in the early volcanic pulses of the NW-PCFB. The thicknesses vary from 1.5 to 3.0 m, occurring as compound lava flows spreading over gently sloping sandy surfaces (5°), preserving the Botucatu paleo-erg or causing a slight deformation of it. Rope surfaces are rare, and some were identified on the top of the flows outcropping near Nivaraí vil-

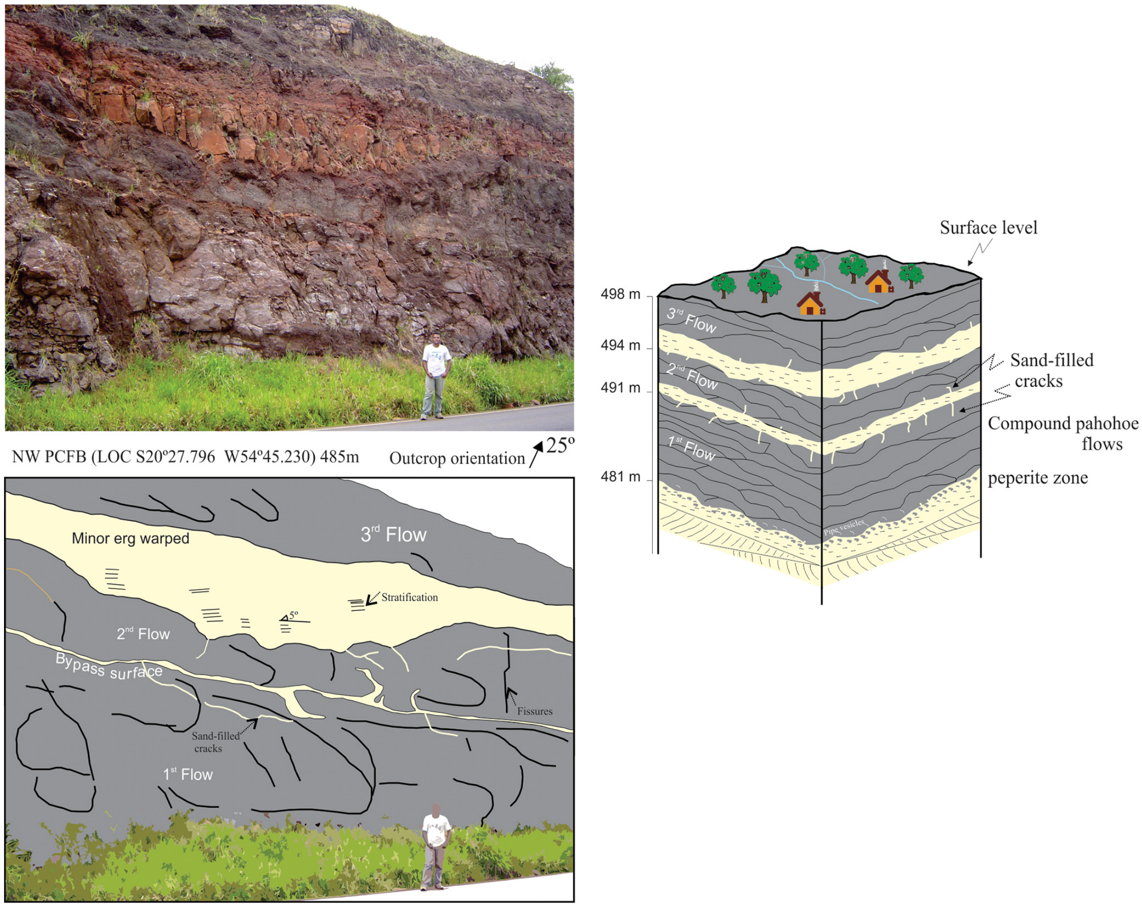

Figure 5. Compound pahoehoe lava flows with interlayered sandstones of the Botucatu Formation, showing bypass sediment features and minor erg deformation.

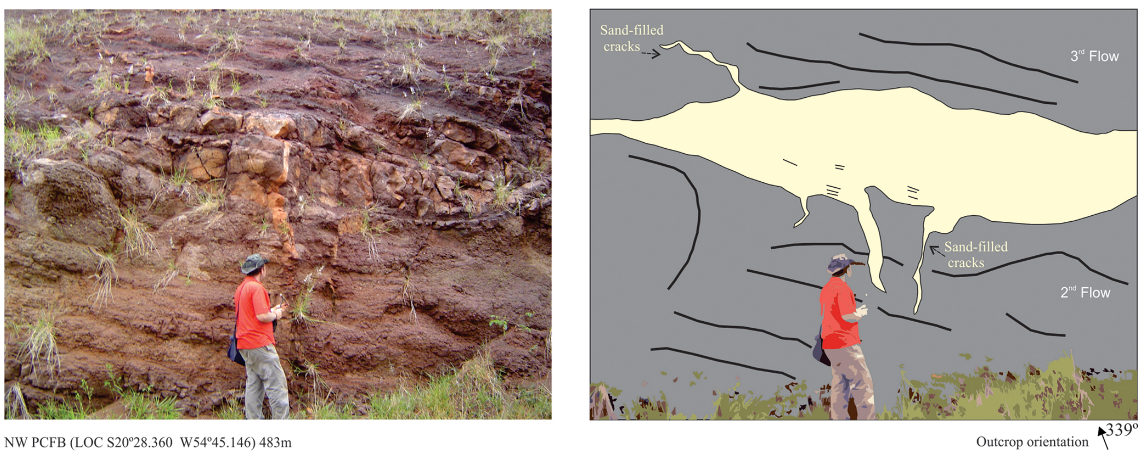

Figure 6. Outcroup with ascending and descending sand-filled cracks in two compound pahoehoe lava flows separated by Botucatu sandstone.

lage (Fig. 4). The individual lobes are small, attaining up to 2.5 m thick. The flows exhibit dispersed vesicles and sand-filled cracks in their base and top borders, where in contact with sediments (Figs. 5, 6, 7), suggesting a pahoehoe-type (P-type) lava flow (Wilmoth and Walker, 1993). The presence of interlayered sandstones is common, showing irregular contacts and varied thicknesses, which are caused by the filling of empty spaces left by the movement of lobes (Figs. 6, 7).

NW PCFB (LOC S22º06.660 W54º47.700) 399 m

Figure 7. Massive simple pahoehoe flows, without sandstone intercalations, exposed in a quarry near the town of Dourados (Fig. 1). The outcrop location is shown in the inset (image from Google Earth).

What is remarkable is the presence of sand-filled cracks, which are associated with the compound pahoehoe lava lobes, occurring either near the peperite zones, in the case of the first volcanic pulse over the sediments, or at the bottom and top of the subsequent flows, when they are separated from each other by a sediment layer. The sand penetration into the base of the first flow achieves a length of up to 30 m, whereas the youngest ones reach 1 m length. The thicknesses of the sand-filled cracks vary from a few millimeters to 10 cm (Figs. 5, 6).

The peperites are observed only in the bottom of the volcanic pile or in the contact of the first layer of basalt flow with Botucatu sandstone, despite breccias of sedimentary rock clasts and sand-filled cracks being observed in different levels of the volcanic pile.

Typical features of the sandstone emplacement just located below the pahoehoe flows are rare. In some locations, the paleodune slip face was identified, as well as striation and chevron marks. The same characteristics were also noticed by Holz et al. (2008) in a study conducted at the northern border of the study area.

The thicknesses of the flows, as well as of all the below sedimentary units, increase towards the interior of the basin (to the E and SE). Near the of Dourados (Fig. 1) the flows are simple pahoehoe (Fig. 6), massive, without sandstone intercalations, and stratigraphically located above those of compound pahoehoe.

Intrusive rocks are rare and have been found in only two mafic dykes 3 m thick, located in the southern area, near Bonito village (Fig. 1), and cutting the Botucatu Formation in a N–S trend parallel to the Assunção Arch located far west. Although some publications have reported a small dyke swarm in the area (Bellieni et al., 1986; Peate et al., 1992), it was not found. Still regarding the intrusive rocks, one sill of about 25 km long and at least 15 m thick occurs in the northern border of the NW-PCFB, intruding into the lower portion of Paraná Supersequence (Fig. 1).

Finally, besides the Quaternary alluvial and colluvial deposits, continental sedimentary rocks of Bauru Basin (Fig. 1) covered the early cretaceous PCFB, in discordant contact, during the Paleogene. The occurrence of basalt clast-supported conglomerates suggests considerable erosion processes in the upper portions of the volcanic piles before the Bauru Basin sediment deposition.

5 Petrography of the basalts

The mineralogy of the investigated rocks is the same for all identified flow types, being generally composed of plagioclase, pyroxene (augite and pigeonite), and opaque minerals (magnetite, ilmenite, and sulphides), with subordinated olivine (most often as pseudomorphs) and apatite. The groundmass is commonly microgranular and rarely micrographic (granophyric texture). There have also been identified alteration minerals like celadonite (quite often), kaolinite, serpentine, biotite, chlorite, calcite, and quartz. The last one is also found as a primary mineral.

The average mode consists of 48 % plagioclase, 33.7 % augite, 0.9 % pigeonite, 7.3 % opaque minerals (magnetite, ilmenite), 1.2 % olivine, and 7.5 % microgranular groundmass. Among the secondary minerals, it is worth highlighting celadonite (1.6 %) and goethite (1.5 %).

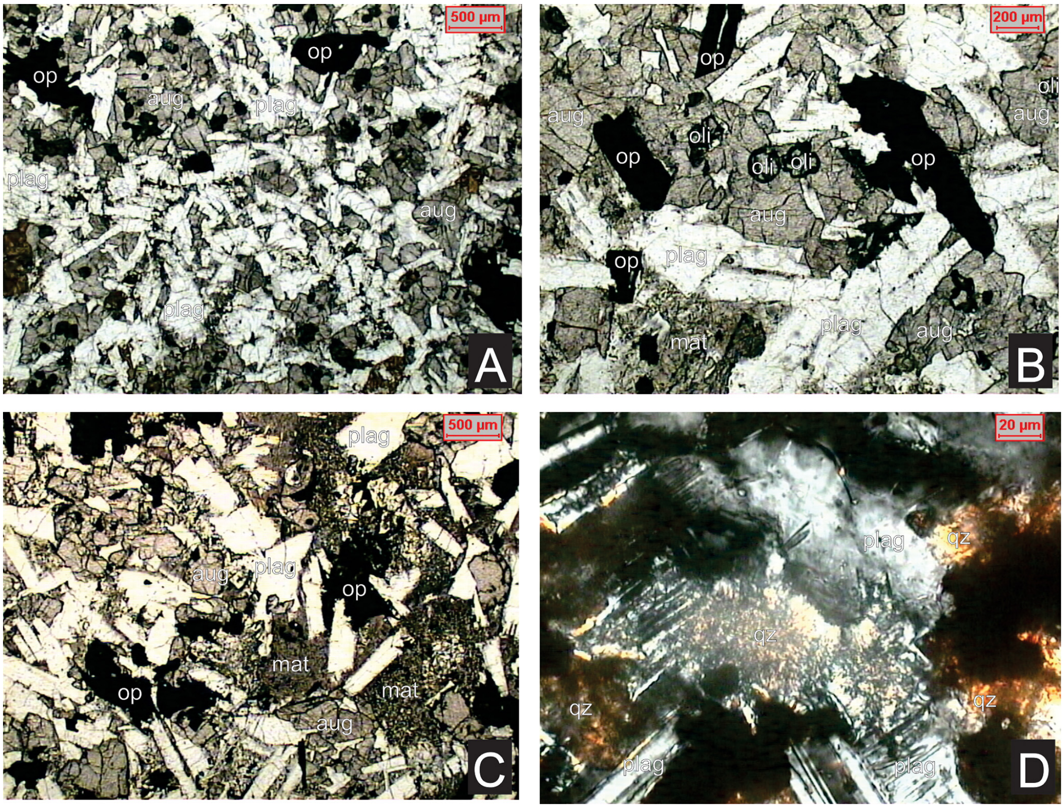

Figure 8. Different textures identified in basalt samples of the NW-PCFB. **(a)** Intergranular, with plagioclase subhedral crystals and interstitial augite crystals (parallel nicols). **(b)** Subophitic, with plagioclase crystals partially included in crystals of augite (parallel nicols). **(c)** Intersertal, with plagioclase crystals corroded by the groundmass (parallel nicols). **(d)** Graphic, with fuzzy aspect micrographic matrix containing quartz (crossed nicols). Legend: plag – plagioclase; aug – augite; op – opaque minerals (magnetite/ilmenite); mat - matrix; oli – olivine.

The presence of vesicles is more common in compound pahoehoe flows than in the massive ones. The segregation structures in the central portion of the lobes, along with microvesicles, located between plagioclase and pyroxene crystals in diktytaxitic texture, are indicative of highly volatile contents in magmas feeding those flows (Jerram and Petford, 2011).

The mineralogical diversity, along with the rheological characteristics of lavas (cooling speed, temperature, viscosity, volatile content, among others), generates a significant variety of textures (Fig. 8). The most common intergranular ones and their subophitic and ophitic variations are associated with rocks that cooled slowly, as evidenced by the size and shape of the mineral phases. Intersertal (with plagioclase crystals corroded by microgranular matrix) and graphic (characterized by an intergrowth of feldspar and microgranular quartz with vermicular or dendritic forms) textures are also noticed, indicating magmatic differentiation processes, with separation of rich-volatile residual liquid forming anomalous mineral phases (quartz, potassic feldspar) for a basic lava.

6 Major, minor, and trace element geochemistry

The NW-PCFB is still lacking in detailed geochemical studies; thus, additional major, minor, and lithophile trace element abundance data were obtained for whole-rock basalt samples (Table 1). All the samples analyzed for major and trace elements are fresh and have loss on ignition (LOI) values lower than 2.5 wt %. Bulk-rock compositions, recalculated on an anhydrous basis, range from sub-alkaline basalt to basaltic andesite according to the total alkali versus silica (TAS) classification (Le Bas and Streckeisen, 1991; Fig. 9). According to the classification for the PCFB flows proposed by Peate et al. (1992), 20 samples belong to Pitanga, 12 to Ribeira, and 4 to Paranapanema magma type.

As a whole, the NW-PCFB rocks have moderately evolved compositions, with MgO contents varying between 6.5 and 3.3 wt %. Compositionally, the analyzed rocks exhibit a tholeiitic affinity, presenting high Fe / Mg ratios (Fe_2O_{3t} / MgO ∼ 2.1–4.6) for relatively high silica contents (SiO_2 = 50–53 wt %). The tholeiitic nature is reinforced by the modal mineralogy of the rocks, with the presence of two pyroxenes (augite and pigeonite).

Table 1. Chemical analyses, magma types, lava flow characteristics, and locations of representative basalt samples of the NW-PCFB.

Magma type Pahoehoe type Sample	Pitanga Simple KS 730	Pitanga Simple KS 731	Pitanga Simple KS 732	Pitanga Simple KS 733	Pitanga Simple KS 738	Pitanga Simple KS 742	Ribeira Compound KS 739	Ribeira Compound KS 741	Ribeira Compound KS 745	Ribeira Compound KS 779	Ribeira Compound KS 830	Ribeira Compound KS 841
SiO_2	51.44	50.30	51.15	50.70	50.45	50.37	51.10	50.80	50.79	50.79	49.98	49.91
TiO_2	3.58	4.18	3.68	3.77	3.78	3.98	1.79	1.82	2.20	1.82	1.74	1.80
Al_2O_3	12.64	12.92	12.53	13.34	13.08	12.69	13.39	13.75	13.37	13.34	13.31	13.13
$Fe_2O_{3\,(t)}$	15.86	15.58	15.54	15.22	15.11	15.34	14.12	12.99	15.03	13.89	13.87	13.88
MnO	0.20	0.21	0.21	0.17	0.20	0.22	0.23	0.21	0.22	0.22	0.21	0.23
MgO	3.44	3.98	3.51	3.59	4.22	4.02	5.69	6.00	5.54	6.32	6.31	5.95
CaO	7.72	8.24	7.82	8.33	8.50	8.07	10.12	10.36	9.34	10.16	10.13	9.88
Na_2O	2.73	2.53	2.70	2.58	2.62	2.60	2.17	2.21	2.31	2.24	2.16	2.12
K_2O	1.81	1.56	1.76	1.45	1.41	1.64	0.85	0.81	0.99	0.84	0.73	0.94
P_2O_5	0.68	0.53	0.68	0.42	0.41	0.58	0.21	0.21	0.25	0.21	0.19	0.20
LOI	0.81	0.85	1.20	1.18	1.08	1.09	0.68	1.23	0.95	0.83	0.81	1.23
Sum	100.91	100.88	100.78	100.75	100.86	100.60	100.35	100.39	100.99	100.66	99.45	99.26
Latitude (S)	22°6.66′	22°6.66′	22°8.7′	21°38.58′	20°26.46′	20°25.14′	20°23.58′	20°25.2′	19°52.68′	20°26.1′	18°32.4′	20°33.36′
Longitude (W)	54°47.7′	54°47.7′	54°49.44′	55°7.38′	54°46.5′	54°51.48′	54°40.26′	54°44.28′	54°26.52′	54°44.4′	53°11.94′	54°39.9′
Height (m)	399	399	382	375	394	342	478	505	440	440	568	496
$Ba^{(1)}$	645	645	571	531	521	578	256	274	336	302	261	279
$Rb^{(1)}$	34	36	34	35	27	27	19	13	25	25	16	22
$Sr^{(1)}$	417	413	405	413	417	398	246	277	280	262	281	276
$Zr^{(1)}$	243	228	253	236	233	246	114	138	158	134	123	127
$Y^{(1)}$	36	43	48	35	41	43	26	31	35	25	29	29
$Nb^{(1)}$	23	30	24	20	22	22	8	13	12	13	9	9
$Cr^{(1)}$	49	75	78	43	38	47	135	94	117	113	177	113
$Ni^{(1)}$	18	18	29	20	21	26	55	57	46	53	68	54
$La^{(2)}$	192.8	170.0	153.2	143.0	134.6	156.5	71.3	74.3	95.4	72.2	69.6	72.6
$Ce^{(2)}$	164.4	145.7	130.3	118.1	115.2	135.2	60.8	63.3	82.1	61.2	58.6	61.2
$Nd^{(2)}$	117.3	108.5	95.8	89.7	84.7	96.1	44.6	44.2	57.3	45.1	43.8	45.1
$Sm^{(2)}$	80.5	71.5	62.4	60.7	56.8	65.5	31.8	32.0	42.2	32.5	31.5	32.4
$Eu^{(2)}$	65.4	57.5	52.0	52.2	48.8	27.2	28.2	54.9	34.8	27.2	27.2	27.7
$Tb^{(2)}$	46.0	42.7	37.7	37.7	35.2	23.5	22.7	37.1	29.4	23.8	23.5	23.8
$Yb^{(2)}$	26.5	24.1	21.3	21.4	20.1	18.1	17.8	21.9	22.7	17.8	17.6	18.0
$Lu^{(2)}$	25.6	22.8	20.3	20.3	18.7	17.5	17.5	21.1	23.2	17.5	16.7	17.5
Eu / Eu*	1.04	1.07	1.04	1.01	1.01	1.01	1.06	1.02	1.07	1.08	1.05	1.06
Ti / Zr	88	110	88	96	97	97	94	80	83	82	86	86
Ti / Y	595	582	461	648	554	557	414	355	377	437	370	378
Zr / Y	7	5	5	7	6	6	4	4	5	5	4	4
Sr / Y	12	10	8	12	10	9	9	9	8	10	10	9
Ba / Y	18	15	12	15	13	13	10	9	10	12	9	10
$(La / Lu)_n$	7.5	7.5	7.5	7.0	7.2	7.4	4.1	4.2	4.1	4.1	4.2	4.2
$(Sm / Yb)_n$	3.0	3.0	2.9	2.8	2.8	3.0	1.8	1.8	1.9	1.8	1.8	1.8
$(La / Yb)_n$	7.3	7.1	7.2	6.7	6.7	7.1	3.9	4.2	4.2	4.0	3.9	4.0
$(La / Sm)_n$	2.4	2.4	2.5	2.4	2.4	2.4	2.2	2.3	2.3	2.2	2.2	2.2

* Major and minor element oxides (wt %) were determined by X-ray fluorescence, whereas trace element concentrations (ppm) were obtained by X-ray fluorescence (1) and ICP-MS (2); $Fe_2O_{3(t)}$ corresponds to the total Fe present in each sample; LOI stands for loss on ignition; REE abundance ratios normalized to chondrites (McDonough and Sun, 1995).

Major and minor elements, against MgO, considered as representative of the magmatic evolution of the rocks, show how the concentrations of these elements vary in the samples (Fig. 10). The results provide evidence that the majority of the NW-PCFB tholeiites have high-TiO_2 contents (2.6–4.2 wt %), as do most of the basalts from the northern PCFB reported in previous studies (e.g., Piccirillo and Melfi, 1988; Peate et al., 1992; Marques et al., 1999; Rocha-Júnior et al., 2012, 2013). Of this high-Ti group, we can distinguish two magma types which emerge from the major, minor, and trace element compositions, referred to as Pitanga (predominant) and Paranapanema (subordinate) magma types, according to the parameters proposed by Peate et al. (1992). In addition, low-Ti tholeiites (namely Ribeira type; $TiO_2 < 2.3$ wt %) have been found further west of Pitanga and Paranapanema outcrops at the northwestern margins of the Paraná Basin. It is important to note that Ribeira samples are less evolved ($MgO = 6.5–5.3$ wt %) than Pitanga and Paranapanema ones, which have MgO contents of 5.8–3.3 wt %.

As can be seen in Fig. 10, in general, SiO_2, TiO_2, Fe_2O_{3t}, Na_2O, K_2O, and P_2O_5 increase, whereas CaO and Al_2O_3 decrease, with decreasing MgO. Despite some scattering, the trends seem to be compatible with fractional crystallization, displaying in general a continuous evolutionary line, which is consistent with literature data (Bellieni et al., 1984; Piccirillo and Melfi, 1988; Peate et al., 1992; Rocha-Júnior et al., 2013). However, at similar MgO contents, Ribeira rocks contain higher SiO_2 and lower P_2O_5 and K_2O than Pitanga and Paranapanema tholeiites. These geochemical characteristics, along with major and minor element mass balance calculations, rule out differentiation of Ribeira magmas by this petrogenetic process to generate Pitanga basalts (e.g., Piccirillo

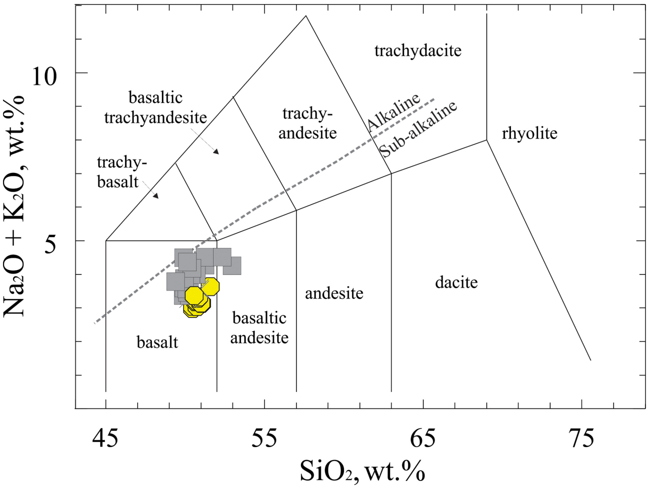

Figure 9. Total alkali versus silica (TAS) diagram (Le Bas et al., 1986; Le Bas and Streckeisen, 1991) used for the nomenclature of basic volcanic rocks of Paraná continental flood basalt province. The dividing dotted line between alkali and sub-alkaline magma series is from Irvine and Baragar (1971). Symbols as in Fig. 1.

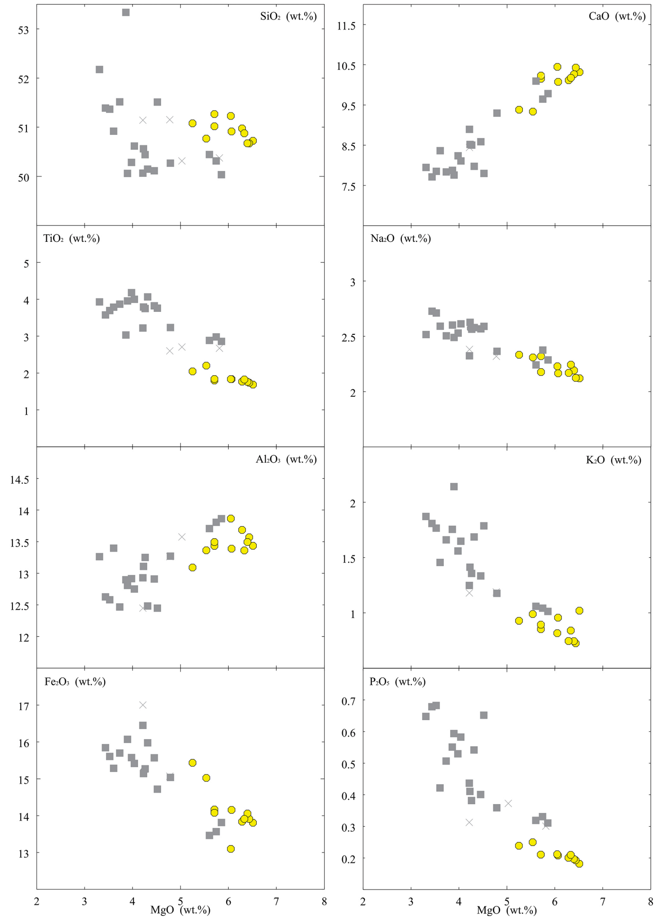

Figure 10. MgO (wt %) versus major (wt %) and minor (wt %) variation diagrams of the investigated tholeiites. Symbols as in Fig. 1.

and Melfi, 1988; Marques et al., 1989, 1999). On the other hand, fractional crystallization mainly controlled by clinopyroxene, plagioclase, and titanomagnetite may account for the geochemical variability inside each basalt group.

The NW-PCFB tholeiites show positive correlations between compatible trace elements (i.e., Ni, Cr) and MgO, although the most evolved samples (Pitanga and Paranapanema) have variable Ni contents. The concentrations of incompatible trace elements such as Nb, Rb, Ba, Zr, and REEs generally increase with the degree of differentiation (MgO; Fig. 11) inside each group of basalts (Ribeira and Pitanga), suggesting evolution by fractional crystallization, reinforcing the behavior of major and minor element oxides. The difference between the two magma types is very clear for the Sr concentrations, with a considerable gap dividing both groups.

REE abundances of the NW-PCFB, normalized to chondrites (McDonough and Sun, 1995), are displayed in Fig. 12, being very similar to those reported in previous studies by Marques et al. (1989) and Rocha-Júnior et al. (2013). The patterns are strongly enriched in light REEs relative to heavy REEs with $(La/Yb)_N = 3.9$–7.3. It should be noted that the HTi rocks investigated in this study have distinctive higher $(La/Yb)_N$ ratios, varying from 6.7 to 7.3, than the Ribeira volcanics, which present $(La/Yb)_N$ from 3.9 to 4.2. The europium anomalies are very slightly positive for both groups of basalts, with Eu/Eu^* varying from 1.01 to 1.07.

7 Lava flow morphology and lava–sediment interaction relationships

As emphasized by Dadd and Van Wagoner (2002), peperites are found both in marine and continental settings, and involve variable rock chemistry, from basalt to rhyolite. In their study of lava flows of Southeastern Canada (Passamaquoddy Bay), they concluded that the main determining factors for the generation of different volcanic clast morphologies are lava viscosity and wet unconsolidated sediment properties. According to these authors, basic lavas tend to generate peperites with more variable clast shapes in comparison to acid ones, which originate blocky clast peperites. In fact, these observations are in agreement with the occurrence of PCFB peperites. In the NW-PCFB, the basic lava interaction with wet, fine-grained sandstone resulted in fluidal peperites, whereas those containing irregular juvenile clasts are found in the central PCFB (Waichel et al., 2007, 2008). In addition, the jigsaw-fit texture peperites associated with rhyolites are reported for the southern PCFB by Luchetti et al. (2014).

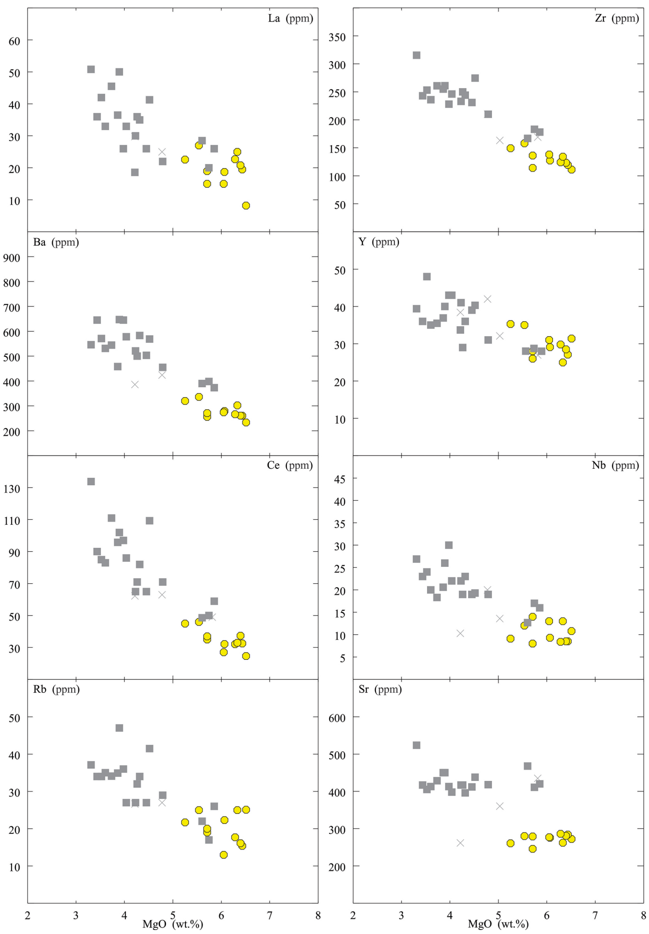

Figure 11. MgO (wt %) versus trace element (ppm) variation diagrams of the investigated tholeiites. Symbols as in Fig. 1.

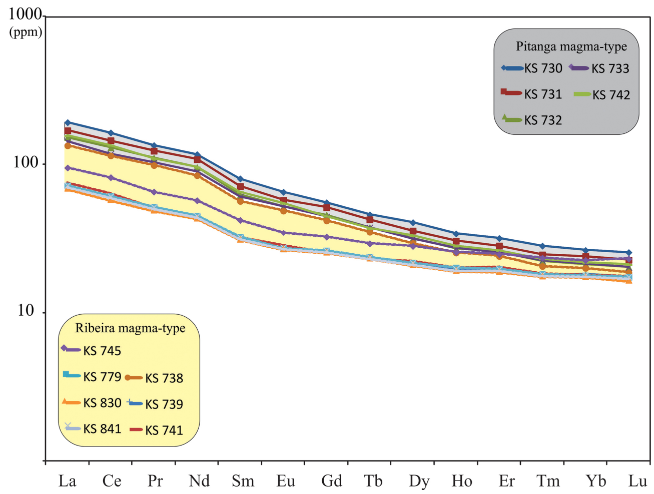

Figure 12. Chondrite-normalized (McDonough and Sun, 1995) rare earth element distribution patterns of Pitanga and Ribeira basalts investigated in this study. Sample location in Fig. 1.

The fluidal peperites associated with pahoehoe lavas of the NW-PCFB seem to be very similar to those of Hawaii. Therefore, it is most likely that the effusive materials have such low viscosities (10^1–10^3 Pa s; McBirney and Murase, 1984) and eruption temperatures ranging near liquidus (∼ 1150 °C; Helz and Thornber, 1987; Cashman et al., 1999). Instead, the rhyolite lavas that generated the peperites reported by Luchetti et al. (2014) have the same characteristics as those found in Passamaquoddy Bay (Dadd and Van Wagoner, 2002), with low temperatures (∼ 800 °C) and high viscosity (10^8–10^{10} Pa s).

As mentioned above, the NW-PCFB peperites are only associated with the first compound pahoehoe flow, although there are flow intercalations with the Botucatu sandstone all over the area. Thus, if the peperite generation were not related to wet unconsolidated sediments, this same feature would also appear in the upper contacts of the interlayered sediments with the compound pahoehoe flows, and not just in the first contact with the sandstones. In addition, the low-angle stratification (5°) of the sandstone corroborates the inter-dune field environment, with no significant variation of the paleotopography in the region.

The presence of water in the Botucatu desert is a controversial issue, since it is generally recognized as a huge, hot, and high-pressure desert system (e.g., Kocurek and Haveholm, 1993). However, its limits were probably subjected to larger variations in weather conditions during the Jurassic and Early Cretaceous periods. The sedimentation environment would be locally modified by three factors: (a) atmosphere, which would be changed by the PCFB's own volcanism; (b) geographical position that allowed the presence of climatic transitional areas in the desert boundaries; and (c) nearby mountains, allowing for possible riverine channels at the borders of the desert. Therefore, the existence of a humid environment at the edges of the desert cannot be ruled out, permitting peperite generation due to lava and wet unconsolidated sandy sediment interactions.

Contrasting to the peperites, which are observed only to be associated with the first flow, the sand-filled cracks take place in all compound pahoehoe flows intercalated with sandstones of the Botucatu Formation. Therefore, the sand-filled crack generation has no direct relationship with the sedimentation environment, occurring in either wet (peperite zone) or dry sediments.

According to the field observations, the sand-filled cracks originated in two stages. Firstly, fissures opened during the inflation and subsequent expansion of pahoehoe lava feeder tubes, whose tips were in direct contact with the sediments (Fig. 13). Thereafter, these cracks were filled with fine sand, still unconsolidated, and may be ascending (subordinate) or descending (predominant). Contrarily to the pipe vesicles, the sand-filled cracks do not necessarily occur in the same direction as the lobe movement, being vertical to subvertical. Note that sand-filled cracks were also described by Jerram

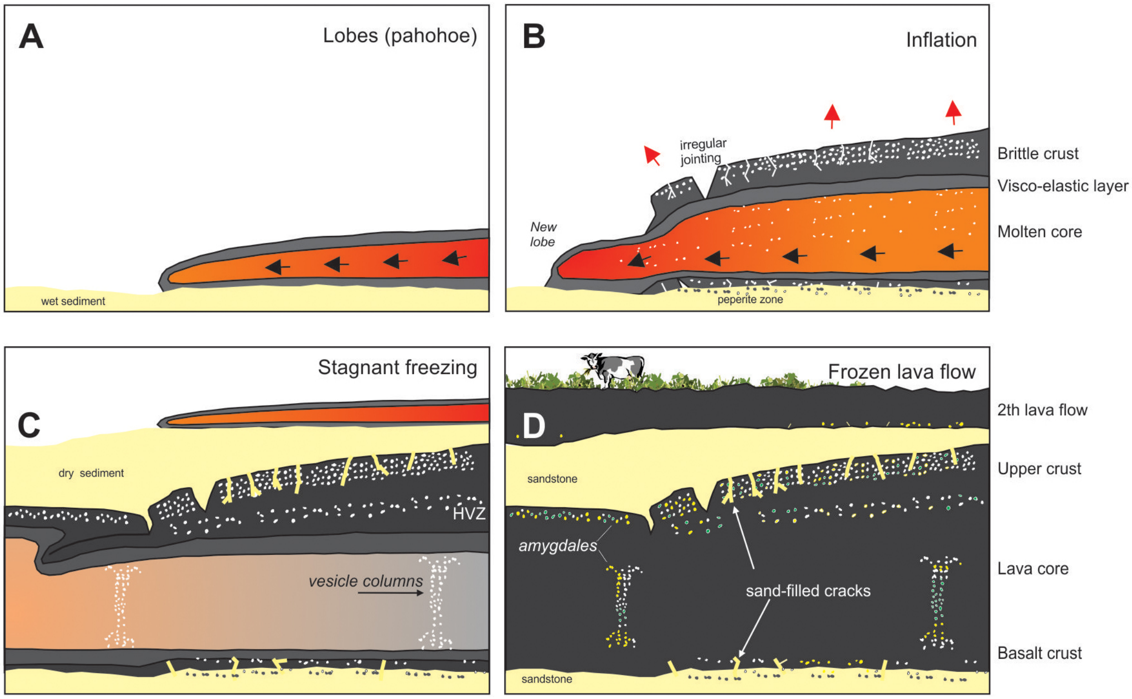

Figure 13. Sketches of sand-filled crack generation observed in flows of the PCFB, integrating the propositions of Self et al. (1996), Jerram and Stolfens (2002), and Jerram and Petford (2011). **(a)** Lobe formation with brittle crust on the surface; **(b)** inflation due to lava injection into the lobe, causing irregular jointing in the basalt upper crust and generating trapped horizontal vesicular zones (HVZ); **(c)** after stagnation, columns of vesicles may form vertical cylinders within the lobe and regular joints may be generated, during the slow cooling of the lava. Before diagenesis, by lithostatic weight sand invades the bottom of the flow (sand-filled cracks) and fills the irregular joints during the sedimentation process, which was synchronous to the lava outpouring. **(d)** All the processes were identified based on vesicle distributions, jointing patterns, and sand-filled cracks. Vertical scale varies from 1 to 8 m.

and Stollhofen (2002) in the Awahab Formation volcanics in the Huab Basin (African counterpart of the PCFB).

On the other hand, the simple pahoehoe flows do not have intercalations with sandstones, corresponding to the top of the volcanic sequence in the region, which is located east of the compound pahoehoe flows. However, the thickness of both volcanic facies architectures could not be determined due to tectonic faulting, which took place during the Pleistocene (Fulfaro and Perinoto, 1994). The tectonism caused the uplift of the region, leading to the Maracaju Mountain formation (Fig. 1; Serra do Maracaju), which is 300 m higher than the general topography. This explains the fact that the samples collected from compound pahoehoe flows of the NW-PCFB border have higher altitudes than those from the simple pahoehoe ones (Table 1). Another consequence of the faulting was the generation of the Ponta Porã Formation (e.g., Fúlfaro and Perinoto, 1994), composed of clastic unconsolidated rocks, rich in basalt clasts, which outcrop to the south of the investigated area.

8 Concluding remarks

This paper reports the main volcanic aspects of the northwestern PCFB, where until now no study has been already, showing not only the flow architectures and the different interaction features with contemporaneous sediments but also the geochemical characteristics of the basalts and their relationship with the magma types of the province. The main conclusions of this investigation are the following:

- In the investigated area, the basalt lavas are in contact and cover the eolic sandstones of the Botucatu Formation of the Paraná Basin, whose sedimentary unit in the African counterpart during the Pangea supercontinent is the Twyfelfontein Formation of the Huab Basin.
- The occurrence of a restricted humid environment in the investigated area is evidenced by peperite occurrences. These wetlands were possibly interdune fields, wherein three main factors might take place in the hydrological cycle: atmosphere change, geographical position, and relief (nearby mountains). These factors could cause the water table to rise and consequently cause its exposition on surface. The most favorable places for the existence of this humid environment were the edges of the Paraná

Basin. Another alternative would be the existence of some small lakes in the Botucatu desert.

- The fluidal peperites of the NW-PCBF are only associated with the first compound pahoehoe flow and were found outcropping by an extent of approximately 80 m long. Juvenile clasts range from submillimeter up to 30 cm long, containing vesicles of variable and fluidal margin sizes. Sometimes the clasts have fine-grained sandstone injections. The wet sedimentary host is a fine-grained sandstone with a low angle of cross-bedding stratification.

- The sand-filled cracks observed in the compound pahoehoe flows are not related to the peperites, but instead to the morphology of the lavas (pahoehoe). The sand-filled cracks were generated by fissures that opened during the lava inflation into the lobes and subsequent expansion of the pahoehoe flow.

- The early basalt P-type pahoehoe flows (containing pipe vesicles), which are in contact with Botucatu sandstones, have the same geochemical signatures of Ribeira magma type. To the east, as well as toward the interior of the Paraná Basin, the pahoehoe flows are overlaid by simple pahoehoe basalt flows, massive and without sand intercalations, presenting identical geochemical characteristics of the Pitanga (dominant) and Paranapanema (very subordinate) magma types.

- In contrast to the central and southern portion of the PCFB, the northwestern area underwent intense tectonic uplift during the Pleistocene, which mainly affected the area of Ribeira basalts, making it difficult to infer their thicknesses. However, the flow stratigraphy was completely defined by the contact relationship with the sandstones of the Botucatu Formation.

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